Design and Development of Integrated Micro Autopilot module with 10 state Sensor Suite and Data Logger for Micro Air Vehicle

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The use of Micro Air vehicle (MAV) for various applications of civil and military domain is exponentially increasing. This is basically due to the ease of acquisition, deployment and commercially viable options. The applications of MAV range from local area surveillance, remote sensing of harmful gases to surveillance applications during natural calamities. With the advancement in the micro electronics technology, many companies in the world are attempting to develop many variants of microelectronic payloads for Micro Air Vehicles (MAV). The micro payloads include functional units like full Inertial Measurement Unit (IMU), programmable controller, data logger and digital as well as analog interfaces. This paper presents the research activity taken up at CSIR-NAL, Bangalore, India in design and development of an indigenous micro Autopilot hardware module with 10 state sensors suite and data logger as an integrated hardware for its application in MAV. Design and development activity concentrated on the selection of suitable programmable controller, compact sensor suite, effective placement and routing for EMI/EMC protection, programmable software resource and easy to handle on-board debugger and data logger system.

Nomenclature

Mag_x	= Magnetometer Sensor Reading along X Axis of sensor in µTesla
Mag_y	= Magnetometer Sensor Reading along Y Axis of sensor in µTesla
Mag_z	= Magnetometer Sensor Reading along Z Axis of sensor in µTesla
A_x	= Accelerometer Sensor Reading along X axis of sensor in m/s^2
A_y	= Accelerometer Sensor Reading along Y axis of sensor in m/s^2
A_z	= Accelerometer Sensor Reading along Z axis of sensor in m/s^2
$P(G_x)$	= Gyroscope Sensor Measurement along X axis of sensor in rad/sec
$P(G_y)$	= Gyroscope Sensor Measurement along Y axis of sensor in rad/sec
$P(G_z)$	= Gyroscope Sensor Measurement along Z axis of sensor in rad/sec
Φ	= Roll Angle of Aircraft in degrees
Θ	= Pitch Angle of Aircraft in degrees
Ψ	= Yaw Angle of Aircraft in degrees

I. Introduction

The present day MAVs provide very efficient and commercially viable platform for military and civil applications like local area surveillance, wireless network deployment, disaster mitigation, and harmful environment detection. The mission requirements vary from application to application. Hence the low cost and low weight MAVs with software configurable resource management integrated with sensors for low weight gyros, magnetometer, accelerometer, pressure sensor are considered to be the solution for varying mission requirements.

The use of commercial available autopilots can reduce the development time but the reconfiguration capability and low weight aspects don't exist in Autopilot systems like Cloud cap, Arduino or Micropilot. The commercial products are easy to use but have limitations in terms of restricting the lower level customer requirement which change from application to application. Low weight Autopilots are required to adapt to different mission requirements which is the need of the hour in the MAV user space. Development of such low cost, minimized form factor, reconfigurable resources and state of the art technology with integrated sensors is detailed and described in this paper.

A. Literature Survey

A comparison of various commercial autopilots like Picolo, Stargate, Kestrel, Micropilot etc. have been given with the relevant weight volume and power budgets in [1]. In [2], the application of "xscale+FPGA" in a small UAV autopilot is presented, where xscale chip-PXA255 of Intel is used. Design of small UAV Autopilot Hardware using DSP is presented in [3]. Complete Design cycle is presented using MP 2128. DSP FPGA Based Hardware-in-the-Loop Testing Platform is described in [4] outlining the necessity of HIL system for Autopilots developed using MEMS Sensors. In [5], the authors have described the development of a system for the rapid prototyping of high level control algorithms using an Arduino based COTS autopilot called ArduPilot, which is capable of controlling multiple vehicle types, including fixed, and rotary wing aircraft as well as ground vehicles. In [6], the authors proposed a cost-effective approach to design an embedded autopilot system for a 4-rotor aerial vehicle which is targeted for autonomous control research, and consists of an onboard system and a ground station. The onboard system interfaced with the vehicle provides data link for sensor measurements and control data. Research in the industry of Autopilot Hardware development for MAV highlights the importance of low weight and low power system development. This paper concentrates the research in this direction of attaining low weight, power and volume requirements.

B. Motivation and Work Flow

One of the outcome of the research is also to realise low weight sensor suite and low weight modular data logger. The low weight sensor suite is developed to be used as a standalone system for various mission requirements. The data logger system is developed to integrate into various platforms for various navigation and environmental parameters data collection. The data logger system uses the Programmable System On Chip (PSoC) platform to exploit the features of reconfigurability for varying mission requirements. The developed Autopilot, Sensor Suite and Data Logger integrated, tested and evaluated on the test platform Slybird. Slybird is an Aerial Platform designed and developed at CSIR-NAL. Integration process is iterative with multiple performance milestones addressed methodically.

In the present research, the focus is on the development of three systems:

1) MAV Autopilot
2) Sensor Suite
3) Modular Data Logger

The above systems have been designed and developed keeping the low weight and reconfigurable factors in focus by integrating PSoC technology with MEMS sensors. The MAV Autopilot module has an on board 3 axis accelerometer, 3 axis gyroscope, 3 axis magnetometer, and, a static pressure and temperature sensor. Interface to various sensors like GPS and ZigBee wireless link exists on the MAV Autopilot. ZigBee Wireless link is used for data , command, control and flight test paramter monitoring. Based on the preliminary design and functional requirement, the system's functionality is listed as follows:

1) Customizable/reconfigurable resource management using PSoC architecture
2) Integrated Digital Sensor Suite with low weight and volume
3) Architecture capability to interface INS/GPS, ZBEE, PWM, Digital bus (I2C, SPI, UART) and non-digital interfaces.
4) Highly reliable embedded system
5) Integrate data link interface for wireless communication up to 2 Km

II. Autopilot Hardware

A. Design Metrics

A set of design metrics were established to help design and guide the development of Autopilot Hardware. The design metrics were identified based on the functional requirements for the 150 mm and 300 mm class MAV. The design metrics chosen are:

1. **Low Weight** **:** The autopilot hardware weight should be less than 12 grams.
2. **Low Volume** **:** The autopilot physical dimensions should be less than 1.5" x 1.5". (Square inches)

3. **Reconfiguration** :The autopilot hardware pin interfaces need to be reconfigurable without impacting the board layout.
4. **Robust** : The autopilot should be highly robust with regard to hardware interfaces.
5. **Low Cost** : It should be possible to manufacture the autopilot for less than INR 20k.

The Architecture of the Autopilot hardware has been designed with regard to these design metrics.

B. Architecture

Micro Autopilot electronic hardware is realized using Programmable Systems On Chip (PSoC), 9 state sensor having 3 Axis Accelerometer (A_x, A_y and A_z), 3 Axis Gyros($P(G_x)$, $P(G_y)$ and $P(G_z)$,) and 3 Axis Magnetometer (Mag_x, Mag_y and Mag_z) and modular micro-SD data logger part of the integrated hardware. Figure 1 shows the features of realized Autopilot hardware. The hardware module has been extensively tested on ground for its sensor data and data logger with limited flight trials. The sensor characterization is in process along with controller as part of the flight tests and ground calibration tests.

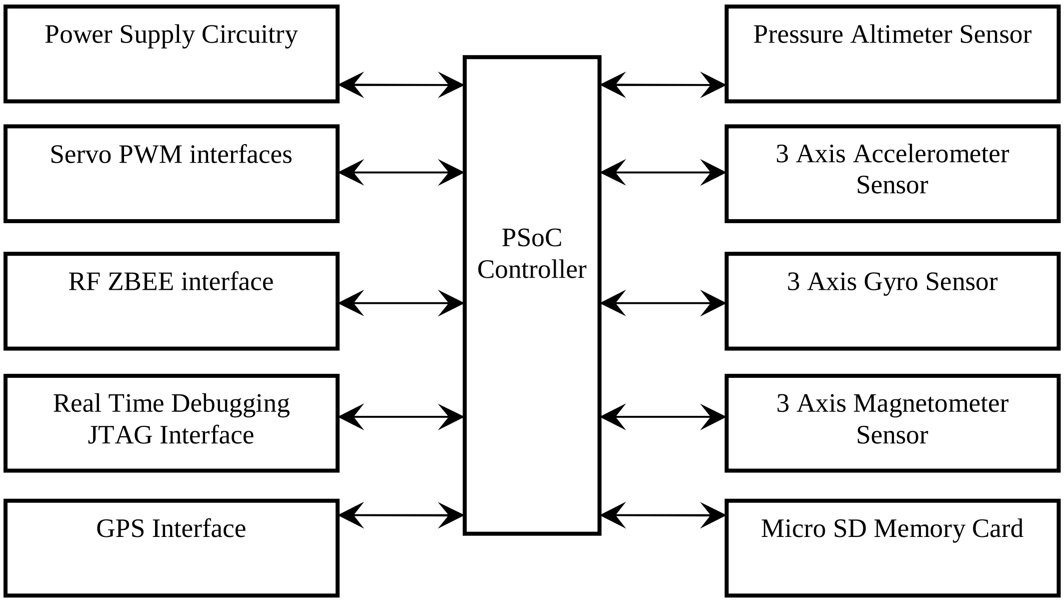

Figure 1. Architecture of Autopilot Hardware

The Autopilot hardware when finally integrated with the control code should be a fully autonomous control system adaptable for any kind of MAV. The weight (10 grams) and size should allow it to be used on in 150 mm and 300 mm class of MAVs as minimum requirements. However the same autopilot can be deployed for the higher class of MAVs also. The Ground Control Station (GCS) serves only to gather and visualize and telemetry data along with manual control. All the peripherals systems like navigation sensors, communications sensors and Telemetry are connected using digital bus interface providing cleaner architecture. The digital interfaces are Inter Integrated Circuit (I2C) or (IIC), Serial Peripheral Interface (SPI) and Universal Asynchronous Receive Transmit (UART) bus. I2C bus is address based and is quite commonly used interface for most of the sensors. The Autopilot module is designed to receive power input of 11.7 V max and the onboard power supply circuit derives the required 5 V and 3.3 V source for controller and sensors.

The system is designed with utmost care to ensure that the highly sensitive sensors are almost free from EMI/EMC interference. Hence the complete Printed Circuit Board (PCB), its routing, placement and various analysis like Signal Integrity Analysis, Power Analysis are carried out as part of the design before the PCB was fabricated. Figure 2 shows the typical analysis results for the Autopilot board at defined boundaries. The analysis shows that the interference levels are not affecting the sensors which are placed away from the interference zone.

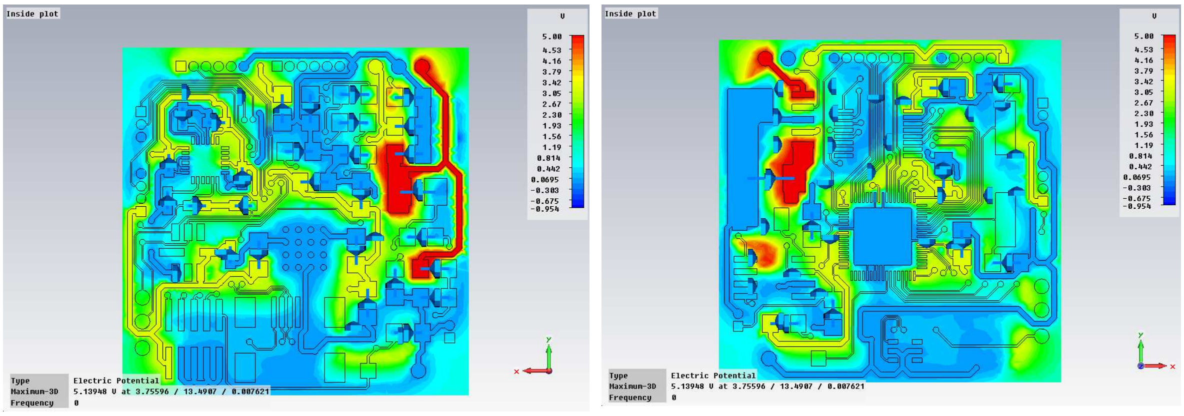

Figure 2. Signal Analysis of the Autopilot bard

After the static test of complete design is completed, the PCB is released for fabrication and later component assembly. The PCB is subjected to cross continuity (Open / short) tests, Power tests, Interface polarity tests and the polarization tests before the same is released for the component assembly. The discrete components are screened for the tolerance clearance wherever required particularly for the sensor and power supply circuitry. Sufficient debug lines, test points and interfaces are provided for the initial Board Support Package (BSP) drivers and application development. Figure 3 shows the assembled Autopilot hardware with all the interface connectors. Figure 4 shows the functional and interface blocks of the Autopilot hardware module.

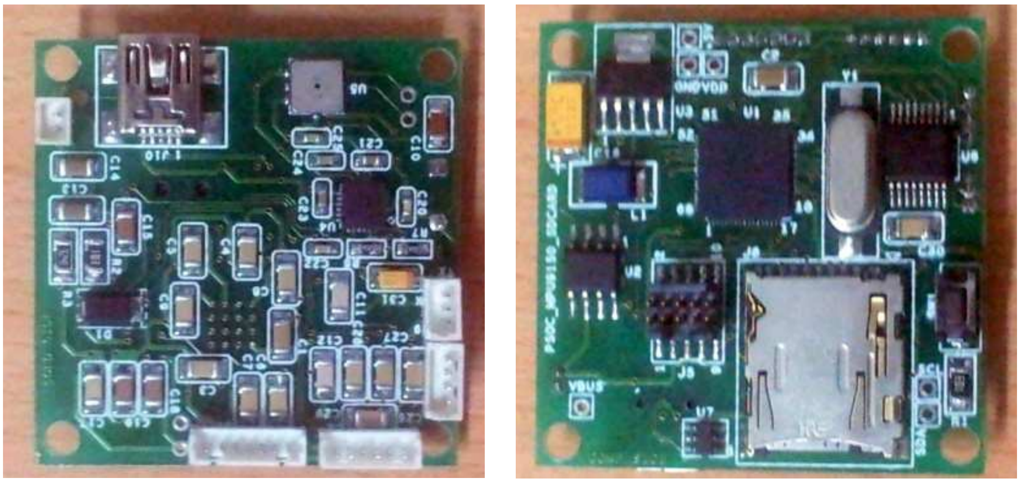

Figure 3. The complete assembled Autopilot hardware

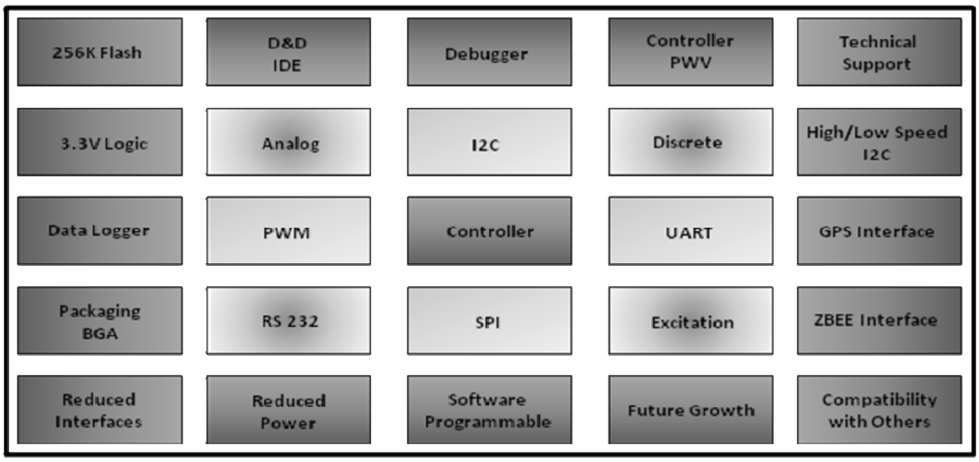

Figure 4. Features of the Autopilot Board Developed

The autopilot hardware was subjected to various levels of testing before the same was integrated to the flying SlyBird aircraft platform. The process for integration testing comprises of following steps:

1. The Autopilot hardware is subjected to power tests to ensure that each of the external interfaces receive the defined voltage levels at the designated interface pins. This test involves powering the board with typical aircraft interface like a battery and testing the various inputs and outputs at different test points on the board.
2. Once Power tests are cleared, then the board is subjected to the basic controller connectivity tests. This test ensures that the controller on board can be connected from external interface for program download and real-time program debug. Once this test is cleared, then the board is ready for the actual program download and testing.
3. A sample pre-tested application is loaded to test all the interfaces. This test ensures that the interfaces for various peripherals on board and external are tested for its initial connectivity and functionality. Once this test is completed then the Autopilot board is free from hardware problems and ready for actual functionality and performance tests.
4. At this stage, the actual application software is downloaded onto the Autopilot board and connected to the Ground Integration tests. These tests can be simple interface tests followed by Hardware In the Loop (HIL) tests using external simulated environment for the aircraft dynamics. This test clears the complete board for aircraft integration requirements.
5. After the above tests, the Autopilot board is integrated onto the flying test bed - Slybird aircraft platform. This aircraft is customized for installing Autopilot, sensors, servo motor, and power control system. However this test is conducted in iterative mode to ensure that the complete controls of the aircraft is integrated after a series of tests one at a time.

C. System Modules and Software Development

1. System Modules

The system modules of the Autopilot Board include the following:

1. PSoC5 Microcontroller
2. Tri Axial Magnetometer HMC5883L
3. Tri Axial Gyroscope ITG3200
4. Tri Axial Accelerometer ADXL345
5. Pressure Sensor BMP085
6. Micro SD Data Logger

PSoC® 5 is an embedded system-on-chip integrating configurable analog and digital peripheral functions, memory and a microcontroller on a single chip with following features:

1. Integrated high-precision 20-bit resolution analog
2. Programmable PLD-based logic
3. 32-bit ARM® Cortex™-M3 CPU up to 67 MHz with PLL
4. Pin to Pin compatible for higher versions
5. Flexible and easy design and development environment
6. JTAG and USB interface for real-time debug.
7. 256KB of flash memory
8. 4 to 8 GB of micro SD memory.

Modularity, Safety, Reconfiguration capability need to be addressed while designing the low weight autopilot hardware. The autopilot requires sensor suite for state estimation and processor for control purpose. MEMS inertial sensors have been chosen to meet the requirements of small size, low eight and low power. All the devices have been integrated in single block of the circuit board as shown in Figure 5 including GPS, Mirco SD Memory and ZBEE modules.

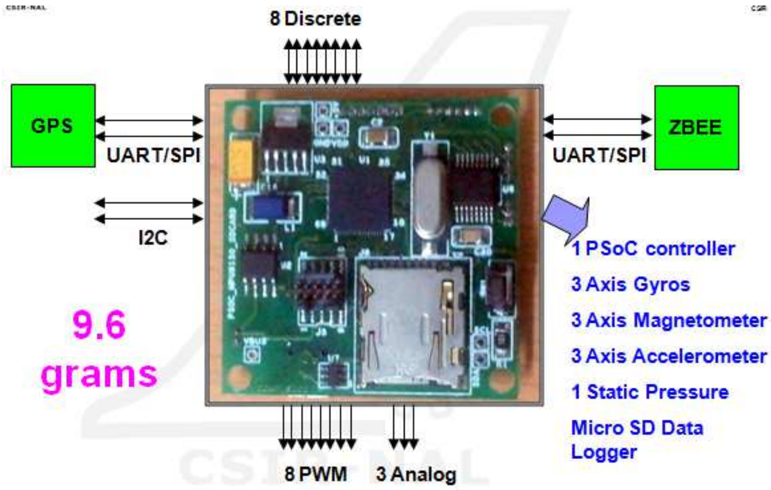

Figure 5. Realized Autopilot Board with sensor suite

2. Software Development:

The software language used is embedded C and the PSoC creator software is used for the design and development of hardware interfaces and porting the application code onto the Microcontroller as full fledged Integrated Development Environment (IDE). PSoC Creator is a state-of-the-art, easy-to-use IDE that allows concurrent hardware/firmware design of PSoC systems based on classical schematic entry [7]. The software is easy to use and supports the important mission of the Autopilot hardware development-reconfiguration. The pins which have been configured for various interfaces like SPI / UART can be reconfigured very easily using software without an impact on the hardware design. The Graphical User Interface (GUI) for PSoC Creator IDE is shown in Figure 6.

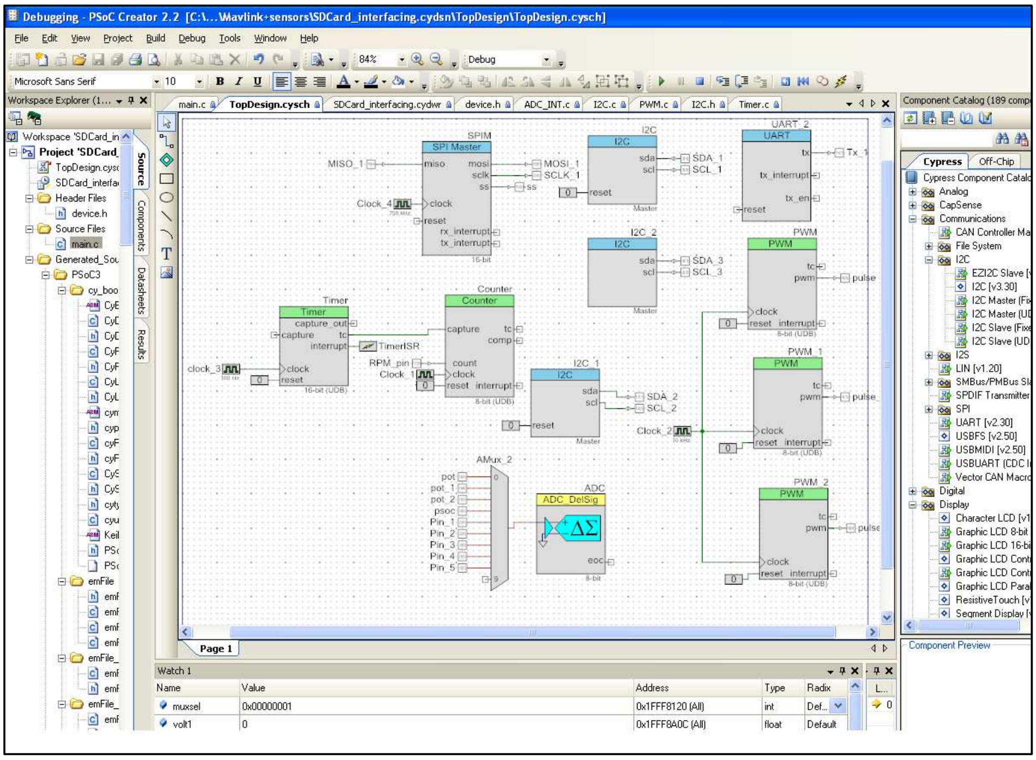

Figure 6. PSoC Creator GUI showing the Hardware Interface Design for the Autopilot

D. Hardware Interfaces

The Autopilot hardware module is designed taking into account the requirement for different types of interfaces like analog, digital, discrete, PWM, I2C, SPI, UART and JTAG. These interfaces are required for various sensors like Infrared (IR), SONAR, Temperature and Humidity, Gas Sensors, Force Sensor, RPM sensor apart from conventional flight navigation sensors like current sensors, acceleration sensors, Pressure altimeter sensor, Gyro sensor, Magnetometer sensor, Airspeed sensor, GPS and Telemetry for mission oriented applications. The advantage of using the PSoc5 system as the controller board is that the hardware pins can be reassigned to a new interface if the situation demands without causing any change to the existing PCB.

List of Interfaces-

1. PWM
2. UART
3. SPI
4. I2C
5. Discrete
6. Digital
7. Analog

1. PWM: Pulse Width Modulation (PWM) interface is provided to interface with the servo motors and also propeller of the aircraft. In the present design, 8 general purpose IO pins have been configured as the PWM interfaces. The PSoC5 Microcontroller provides advantage of reconfigurabilty based on the requirement that, the number of PWM pins can be increased or decreased without changing the hardware design of the board.

2. UART: Universal Asynchronous Receiver/Transmitter (UART) Interface is provided to interface with the GPS system.

3. SPI : Serial Peripheral Interface Bus is provided to interface with the ZigBee transceiver.

4. I2C : The Inter Integrated Circuit Bus is a versatile bus and all the latest sensors being developed come with an I2C interface. Here it is configured for the IMU sensor and other environmental sensor data.

5.Discrete: Discrete Interfaces have been provided so as to enable reading or commanding via discrete inputs.

6.Analog: Analog Interfaces have been provided to accept measurements into data logger from the analog sensors like transducers and Current/Voltage sensors.

The Autopilot designed and developed has met the design criteria, requirements and the consolidated features of the as shown in Figure 4**.**

III. Sensor Suite

10 DoF or 10 State Sensor suite is realized and embedded on the same Autopilot hardware providing direct access to the complete sensor data. The system has unique features like fully digital communication, provision for embedding calibration data for each sensor having low weight, power and volume. However, in the event of special mission requirements related to positioning of sensor at different places from the main flight control board, a 10 DoF sensor suite has been designed and developed separately with the same set of sensors as of onboard Autopilot module. This separate sensor suite also has digital interface bus using I2C. The realized sensor suite at CSIR-NAL is as shown in Figure 7. The complete analysis as described for the main Autopilot module was also carried out for this sensor suite module. The realized total weight of the sensor suite is around 1.32 grams. The board can be integrated on to any controller with master I2C capability. This module was integrated onto Slybird and Hang Glider flying platforms. Preliminary results are quite satisfactory.

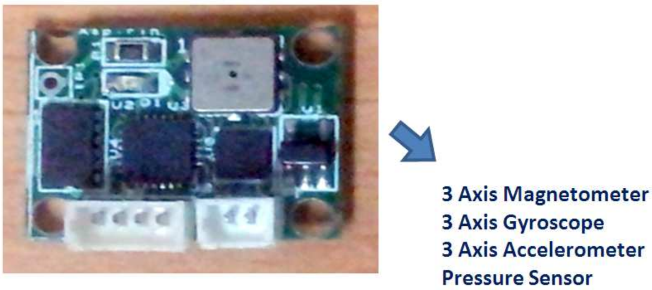

Figure 7 Realized 10DoF or 10 State Sensor Suite

IV. Modular Data Logger

The flight data is of utmost importance for performance analysis and validation requirements. Typically a separate data logger will be integrated onto the MAV for data logging applications. However in this case, modular data logger is on-board the same Autopilot hardware. The Micro SD card is used as data logger to meet the requirements of both the flight data as well as sensor data specific to missions. The Modular Data Logger has been designed to accept data from the following sensors:

- 3 Axis Accelerometer, 3 Axis Magnetometer, 3 Axis Gyroscope
- Static Pressure Sensor
- Current Sensor and Voltage Sensor
- RPM Sensor
- Gas Detection sensors
- IR and SONAR sensor
- Temperature and Humidity Sensor
- Airspeed Sensor

The data is captured at variable rates for different sensors and recorded onto the micro SD card for post flight analysis.

V. Integration and Testing of Complete Solution

The complete Autopilot module along with sensor suite was integrated to the Slybird flying platform as piggyback configuration with main Autopilot module. This experiment was conducted initially to check the performance of the sensors with the onboard reference sensor. Later the same was used to establish the functionality of the module as standalone data collection mode. The design of autopilot hardware module is complete only after the system is flight tested on the flying platform (aircraft). The technical features of the chosen platform are as shown in Table 1.

Table 1. Specification of Test Aircraft

Wing Span	1.6m (5.2 ft)
Length	1.3 m (4.2 m)
Weight	~2.6 kg
Range	around 10 km
Endurance	45–60 minutes
Speed	10-30m/s, 36-108 kmph
Operating Altitude	30m-300 m (100-1000 ft) AGL, 15,000 ft ASL max launch altitude
Payloads	Forward looking daylight or thermal Camera with stabilization.
Launch and Recovery	Hand-Launched and Deep Stall Landing

CSIR-NAL is flying the Slybird which is mini UAV as shown in Figure 8. This vehicle is chosen to integrate the Autopilot along with sensor suite to test the functionality and performance issues in piggyback mode. The platform was used to fly the developed autopilot hardware and the data from various sensors were captured to study the sensor characteristics. After validation of the sensor and basic hardware module of Autopilot board, the application software including the Control Law for autonomous navigation will be ported onto the same hardware. However the control law porting and validation is not in the scope of this paper.

Figure 8 Test Aircraft NAL-Slybird

VI. Results

The Autopilot hardware was integrated and flown in NAL-Slybird to test the interface integrity and the performance of the sensors. The test was conducted at Bangalore where the Altitude above Sea Level is around 900 m. Couple of flight tests was conducted and huge set of data was collected using onboard microSD memory used as Modular Data Logger.

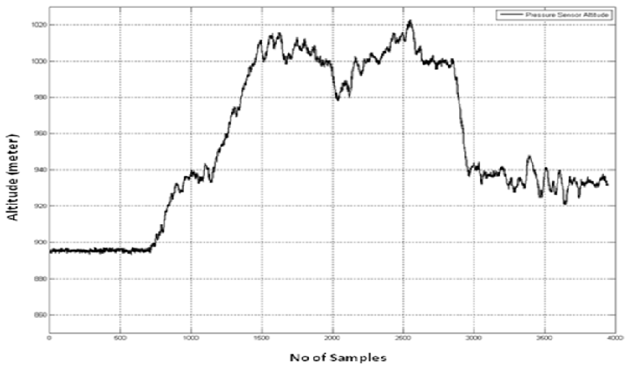

Figure 9 Altitude Profile (ASL) for the Test Flight

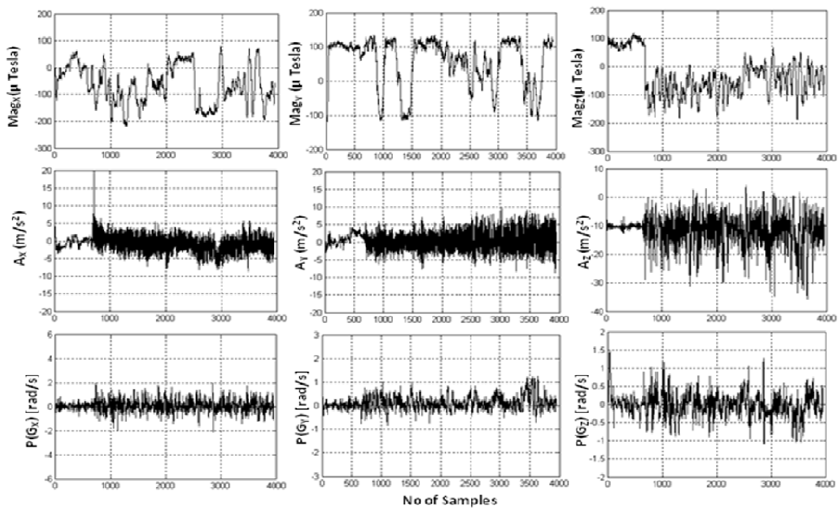

Figure 10 Sensor readings for Magnetometer, Accelerometer and Gyroscope

The data then analyzed in raw as well as post processed mode for various parameters. The Altitude profile for test flight is shown in Figure 9 and other sensor data are as shown in Figure 10 for Magnetometer, Acceleration and Rates. The Roll, Pitch and Yaw have been estimated using the traditional DCM and EKF algorithm developed is as shown in Figure 11, the details of which are not in the scope of this paper. The values have been estimated onboard the Autopilot module which is used for the flight control and also simultaneously stored in the data logger present.

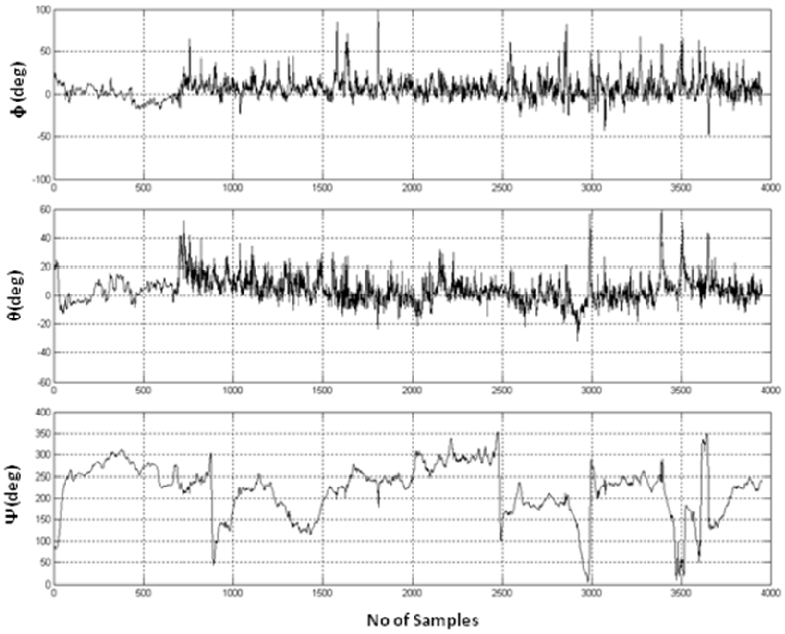

Figure 11. Roll, Pitch and Yaw of Aircraft estimated onboard(w/o filtering)

VII. Conclusion

This paper presented a PSoC5 based Autopilot hardware architecture, Sensor Suite and Modular Data Logger. The systems focused on minimizing the weight of hardware for Micro Air vehicle operations. The PSoC based configuration gives flexible and efficient resource management which reduces the power consumption of the complete module enhancing the endurance of the flight. The complete Autopilot hardware module with 10 state sensor suite along with all the required interfaces for typical MAV configuration is realized with a weight budget of 9.6 grams compared to 12 to 15 grams in the industry. The separate sensor suite is realized with weight budget of 1.23 grams.

The contributions of this research are stated as follows:

1. Development of Hardware for three sub systems of MAV: Autopilot, Sensor Suite and Modular data Logger- PSoC 5 enables reconfigurable interface control under a weight budget of 10 grams and the other design metrics also satisfied.
2. System integration and functional verification : The system has been test flown and initial performance characterization is captured using NAL-Slybird flying platform and the results are quite satisfactory.

Acknowledgments

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